PHOTOGRAMMETRIC CALIBRATION AND POINT DETERMINATION USING A DIGITAL CCD CAMERA

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ABSTRACT:

Digital CCD cameras are increasingly being used for photogrammetric applications, mainly for digitizing film hardcopies and in close range environments (robot vision, machine vision). A prerequisite for these tasks is a sufficient geometric and radiometric accuracy of the camera.
In this paper we assess the geometric accuracy potential of a digital CCD camera, the ProgRes 3000, for photogrammetric point determination using the selfcalibration approach in conjunction with a small testfield. 8 images of this testfield with 29 well defined points were recorded. Measurement of the image coordinates of these points was carried out using two different methods: a chain code algorithm and least squares matching. The results are reported and discussed.
Furthermore, the impact of the camera calibration on object point determination is demonstrated. Achieved empirical standard deviations of the control points lie in the range of 30 μm or 1:20.000 in object space.

Key words: Robot vision, digital CCD camera, calibration, close range photogrammetry.

1. INTRODUCTION

Charge Coupled Device (CCD) cameras are increasingly being used in photogrammetry for direct image acquisition and for digitization of hardcopy film. In general the interior orientation of these cameras is not known, it changes, when the focusing is changed, and lens distortion has to be taken into account. Therefore, the cameras must be calibrated to meet photogrammetric accuracy requirements. A complete calibration includes radiometric aspects (e.g. the compensation of different sensitivity of CCD sensor cells) as well as geometric ones.
Geometric calibrations of CCD cameras with video output (analogue signal) are reported from a number of authors. Gülch /1984/, Dähler /1987/, and Luhmann, Wester-Ebbinghaus /1987/ investigated the image quality (line jitter, blooming etc.). Beyer /1987/ treated various aspects of the geometric calibration using a three dimensional testfield. Lenz /1987/ presented a fast multi-step calibration procedure for applications at television field rate. However, major problems were observed in conjunction with the necessary A/D conversion of the video signal. Dähler concludes, that "it is ... strongly recommended to transfer the information from CCD cameras digitally" /Dähler 1987, p. 59/. Only few reports on a photogrammetric calibration of such digital CCD cameras exist /Bösemann et al. 1990; Beyer 1991; Edmundson et al. 1991; Heipke et al. 1991/.

This paper deals with the geometric accuracy potential of the ProgRes 3000 /Lenz 1989/, a digital CCD camera. Our approach using selfcalibration in conjunction with a small testfield is explained. 8 images of this testfield with 29 well defined points were recorded. Measurement of the image coordinates of these points was carried out using two different methods: a chain code algorithm and least squares matching. The results are reported and discussed. Finally an example for the photogrammetric evaluation of three dimensional objects is given. Achieved empirical standard deviations of the control points lie in the range of 30 μm or 1:20.000 in object space.

2. SELFCALIBRATION OF THE PROGRES 3000

2.1 The ProgRes 3000 camera

The ProgRes 3000 camera /Lenz 1989/ is a digital CCD camera with a sensor chip of 512 * 580 pixels at a pixel size of 17 μm * 11 μm. High resolution images are generated from a number of successively taken images, so called partial images. For each partial image the CCD sensor is moved a fraction of the distance between two pixel centres using a piezo-controlled aperture displacement (PAD). The amount of this displacement, and thus the image resolution is programmable and can be performed with a root mean square error of about 0.2 μm /Lenz, Lenz 1990/. This microscanning procedure results in a resolution of up to 3072 * 2320 pixels and a pixel size of down to 2.83 μm * 2.75 μm. Additionally, colour imagery can be captured. At maximum resolution the colour image acquisition can be performed in a few seconds. It has been shown that digital images of static objects can be acquired with the same image quality as hardcopy diapositives.

2.2 The mathematical model

Selfcalibration is performed based on the well known collinearity equations. Corrections for the improvement of the coordinates of the principal point and the principal distance are introduced. Additional correction terms dx and dy for the measured image coordinates x and y respectively are formulated to model lens distortion. Higher order polynomials can be used to correct for other systematic image deformations from the central projection.

If parameters for radial and tangential lens distortion are to be determined, dx and dy can be expressed as:

$$dx = A_1 (r^2 - r_o^2) x + A_2 (r^4 - r_o^4) x + B_1 (y^2 + 3x^2) + 2 B_2 x y$$

$$dy = A_1 (r^2 - r_o^2) y + A_2 (r^4 - r_o^4) y + 2 B_1 x y + B_2 (x^2 + 3 y^2)$$

with:

x, y	image coordinates
A_1, A_2, r_o	parameters for radial lens distortion
B_1, B_2	parameters for tangential lens distortion

$$r^2 = (x - x_o)^2 + (y - y_o)^2$$

x_o, y_o coordinates of principal point

From the observations (image coordinates of a number of tie points) the estimation of the unknown parameters (corrections for the coordinates of the principal point and the principal distance, A_1, A_2, B_1, B_2, the elements of exterior orientation and the object coordinates of the tie points) is performed according to the least squares principle. Control information can be introduced in addition to the image coordinates in order to define the elements of the datum (three translations, three rotations and scale).

2.3 Image acquisition

For the geometric calibration of the ProgRes 3000 a relatively small three dimensional testfield with 29 equally spaced points was used. The size of the testfield is approximately 0.60 m * 0.60 m, the maximum height difference is 0.23 m. The signals are black circles on a white background and have a diameter of 3 mm each. The coordinates of the 29 points were determined photogrammetrically using a Wild P31 metric camera and a Rollei Réseau Scanner. The resulting standard deviations of the control point coordinates are about 12 μm in X, Y, and 25 μm in Z.

Eight images of the maximum resolution of 3072 * 2320 pixels were taken with the ProgRes 3000 equipped with a standard 16 mm lens at a distance of about 1.6 m, yielding an image scale of about 1:100. Thus, one signal covered about 10*10 pixels. Four of the eight images were oblique views taken from an angle of about 50

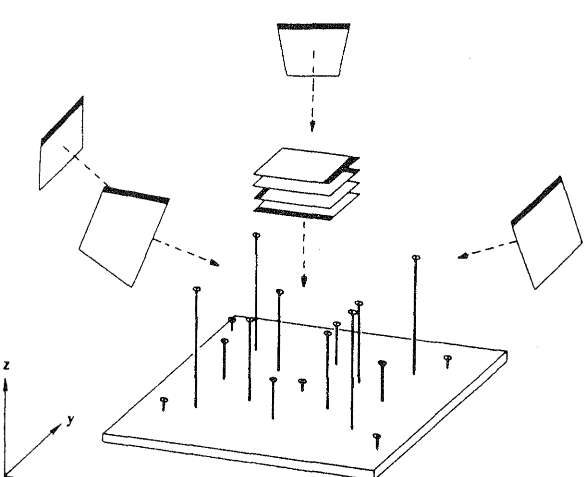

Figure 1: Geometric configuration of image acquisition

degrees. The geometric configuration of the image acquisition is shown in figure 1.

2.4 Determination of image coordinates

Two different procedures were used for the measurement of the image coordinates of the signalized points. One set of image coordinates was obtained using a chain code algorithm /Lenz 1987/. At first, for each image point a surrounding box is drawn interactively. By means of histogram analysis within this window, a greyvalue threshold is automatically determined, discriminating pixels belonging to the image point from those belonging to the background. This yields a closed boundary line passing between image point pixels and background pixels. In the next step, a more precise boundary line is determined separately for the x- and y-axis by means of linear greyvalue interpolation. For the determination of the x-coordinate of the image point only the vertical boundary line elements are shifted, and vice versa. From the two refined boundary lines, the centre coordinates of the enclosed image point are determined with subpixel accuracy by calculating the 0^{th} and 1^{st} order momentums from the line integrals.

A second set of image coordinates of the same eight images was derived using least squares matching /Förstner 1982/. A template showing a black circle with a diameter of 10 pixels on a white background was generated. Although a method for the automatic detection of approximate signal positions in the images can easily be set up, for reasons of simplicity the results of the first described algorithm were used as initial values for the matching procedure. Plausibility checks for the results were carried out as described in Heipke, Kornus /1991/. A theoretical comparison between the two algorithms reveals that

- least squares matching determines the centre of the circular signal as projected into the image, chain code matching determines the centre of the distorted signal; although the difference between the two positions is not significant in most cases, only the first position is correct.
- least squares matching uses all pixels of the signal, chain code matching uses only the signal contour. Thus, in the latter case radiometric errors within the signal (eg. reflections) can be tolerated.
- only least squares matching produces an accuracy estimate for the results.
- chain code matching runs substantially faster.

A comparison between the two sets of image coordinates resulted in a root mean square error of 0.06 μm for each coordinate. From the above observations and these results, it is clear that both algorithms give excellent results for the measurement of image coordinates of signalized points. In a particular project the more suitable algorithm has to be chosen according to additional criteria.

3. RESULTS

3.1 Results of calibration

The two questions to be investigated here were the accuracy of the determined calibration parameters of the ProgRes 3000 and their stability over time. For all computations the bundle adjustment programme CLIC developed at the Chair for Photogrammetry and Remote Sensing, Technical University Munich /Müller, Stephani 1984/ was used.
In order to impose little constraint on the solution, only five control points were introduced, one in each corner of the testfield and one in the middle. In a first comparison both sets of image coordinates were used. Since the results did not show any significant differences, only the coordinates obtained with the chain code algorithm are considered in the following. The calibrations were carried out in three different epochs over three weeks. The results are presented in table 1. For each epoch the values and theoretical standard deviations of the principal distance, the location of the principal point, and the maximum effect of distortion (radial and tangential) are given. Also the estimated standard deviation of the image coordinates σ_o is included. The following conclusions can be drawn from the results:

- A calibration of the parameters of interior orientation and lens distortion is necessary, if precise three dimensional object point coordinates are to be determined. The location of the principal point differs by more than 119 μm (about 40 pixels) from the centre of the chip, the distortion amounts to a maximum of approximately 75 μm (about 25 pixels).
- The results show a very stable behaviour over time. Therefore, a calibration has to be carried out in extended time intervals only.

	epoch 1		epoch 2		epoch 3	
	value	σ	value	σ	value	σ
principal distance	16.067 mm	5 μm	16.067 mm	5 μm	16.064 mm	5 μm
x_o	21 μm	6 μm	19 μm	6 μm	19 μm	6 μm
y_o	119 μm	6 μm	119 μm	6 μm	126 μm	6 μm
dx_{max}	59 μm	2 μm	59 μm	1 μm	59 μm	2 μm
dy_{max}	47 μm	1 μm	47 μm	1 μm	47 μm	2 μm
σ_o	0.39 μm		0.39 μm		0.37 μm	

Table 1: Results of calibration

- σ_o, the estimated accuracy of the image coordinates, lies at about 0.4 μm or 0.15 pixels. This confirms that the measurement of well signalized points can be performed with very high subpixel accuracy.

However, σ_o is significantly higher than the root mean square error of the comparison between the two sets of image coordinates. Thus, a number of error sources has not yet been properly modelled. Some can be named: the accuracy of the sensor movement during image acquisition, and the time stability of the testfield. Less likely are systematic errors in the observations (they should show up in an analysis of the residuals, and didn't), in the applied distortion model (the introduction of higher order polynomials did not improve the results), and in the control points (a free net adjustment resulted in a σ_o of 0.33 μm). Further investigations have to be conducted in order to identify and model the relevant error sources.

3.2 Photogrammetric application example

As an example for the attainable accuracy in object space two conventional photogrammetric evaluations were carried out. Images of the testfield at a scale of approximately 1:100 were acquired using

- two images with parallel optical axes and a distance between the projection centres (baselength) of 0.4 m and
- two convergent images with a baselength of 3 m.

Image coordinates of the signalized points were measured using the chain code matching algorithm, and each pair of images was processed twice, once including the calibrated interior orientation parameters, and once without them. Table 2 shows the results. Empirical standard deviations derived from a comparison with the known testfield are given for each coordinate in object space. The following can be concluded:

- The attainable accuracy in object space lies at 0.02 mm - 0.04 mm in each coordinate for the convergent case. This confirms that digital photogrammetry can compete very successfully with other techniques in high precision measurement tasks.
- The accuracy for the parallel case is worse, especially in the direction of the optical axis (Z coordinate). This is due to the small field of view of the camera. A parallel setup, however, is only necessary, if stereo viewing of the images is of interest. A convergent setup is superior in terms of accuracy.
- The comparison between the results with and without calibrated parameters of interior orientation clearly demonstrates the effectiveness of calibration.

	2 images, parallel setup			2 images, convergent setup		
	s_X [mm]	s_Y [mm]	s_Z [mm]	s_X [mm]	s_Y [mm]	s_Z [mm]
uncalibrated version	3.0	2.8	33.5	1.2	1.0	0.5
calibrated version	0.05	0.11	0.52	0.02	0.02	0.04

Table 2: Results of photogrammetric evaluation

4. CONCLUSIONS AND OUTLOOK

This investigation covered a geometric calibration of the ProgRes 3000 camera and an example for a photogrammetric evaluation. It could be shown that the parameters of interior orientation and lens distortion can be determined precisely by the calibration procedure and they were found to be stable over time. Accurate object point coordinates can be obtained, if a rigorous mathematical model including the calibration parameters is used for the evaluation. Thus, the results show the applicability of the camera for photogrammetric tasks. Further research has to be conducted in order to

- set up an automatic calibration procedure,
- improve the accuracy of the piezo-controlled sensor movement,
- include a radiometric calibration.

The stability over time of the orientation parameters and the accuracy level already reached encouraged us to design a digital photogrammetric close range measurement and evaluation system around the ProgRes 3000, in which images can be acquired, stored, and evaluated in a totally digital data flow using rigorous photogrammetric procedures.

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